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Changing drainage patterns within South Cascade Glacier, Washington, USA, 1964-1992

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Abstract The theoretical patterns of water drainage are presented for South Cascade Glacier for four different years between 1964 and 1992, during which the glacier was thinning and receding. The theoretical pattern compares well, in a broad sense, with the flow pattern determined from tracer injections in 1986 and 1987. Differences between the patterns may result from the routing of surface meltwater in crevasses prior to entering the body of the glacier. The changing drainage pattern was caused by glacier thinning. The migration of a drainage divide eventually rerouted most of the surface meltwater from the main stream that drained the glacier in 1987 to another, formerly smaller, stream by 1992. On the basis of projected glacier thinning between 1992 and 1999, we predict that the drainage divide will continue to migrate across the glacier.

INTRODUCTION

The drainage pattern of water flow in South Cascade Glacier during 1986 and 1987 was revealed by (Fig. 1) by injecting tracers into crevasses and moulins and detecting in which of three proglacial streams the tracer emerged (Fountain, 1992). The meltwater input in each drainage area was compared with the stream discharge from that area and the two values were similar. The striking feature of the drainage pattern is how the water from the upper reaches of the glacier is concentrated into a narrow path that divides the lower glacier into three different drainage basins. We questioned whether this feature resulted from some temporary hydraulic condition or was typical of antecedent drainage patterns. Considering that South Cascade Glacier has been rapidly thinning and retreating (Krimmel, 1989, 1993), the drainage patterns may too be changing.

Hydrological investigations of South Cascade Glacier in 1992 (Vaughn, 1994) indicated that the drainage pattern had changed since 1987. Formerly, stream 3, which drained most of the accumulation zone, had twice the average summer discharge of stream 2, which drained the east side of the lower glacier and much of the ablation zone (Fig. 1). In 1992, the relation was reversed; stream 2 was the largest stream and the average summer discharge was more than twice that of stream 3 (Fig. 2).

To investigate whether the drainage pattern detected in 1987 was typical of the pattern at South Cascade Glacier and whether the relative change in discharge between the two major streams for the period 1987 to 1992 resulted from a change in the pattern of drainage, we examine the theoretical flow patterns of South Cascade Glacier in this paper.

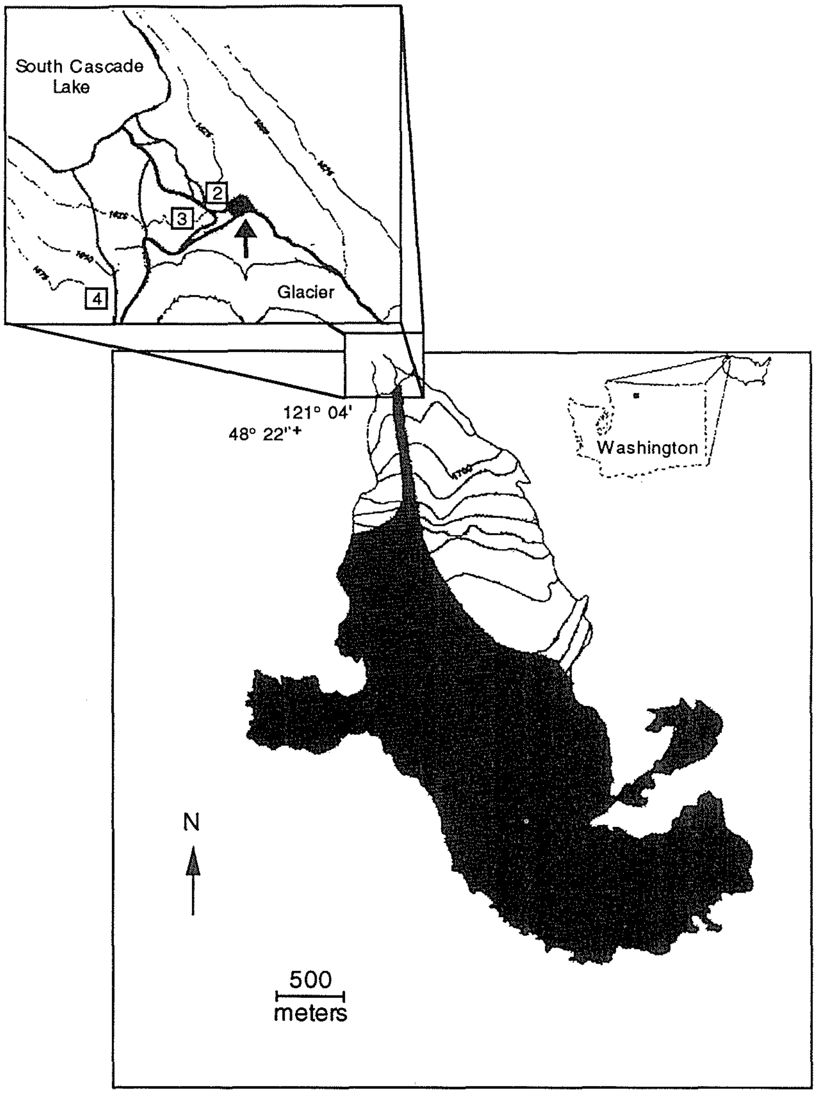

Fig. 1 The drainage pattern of South Cascade Glacier delineated by tracer injections made in 1986 and 1987. Configuration of the streams in 1986 is shown in the inset with stream number. The arrow indicates where stream 2 exits the glacier and enters the proglacial pond.

STUDY SITE AND FIELD OBSERVATIONS

South Cascade Glacier is an alpine glacier about 2.5 km^2 in area and about 3.4 km long. It is located at 48°21'N, 121°3'W, on the crest of the North Cascade Mountain Range in the state of Washington. The glacier is in a maritime environment with annual precipitation commonly reaching about 4.5 m of water equivalent and a mean annual temperature of about 1.3°C (Meier *et al.*, 1971). The glacier is part of the U.S. Geological Survey's benchmark glacier network (Meier *et al.*, 1971) and is the focus of

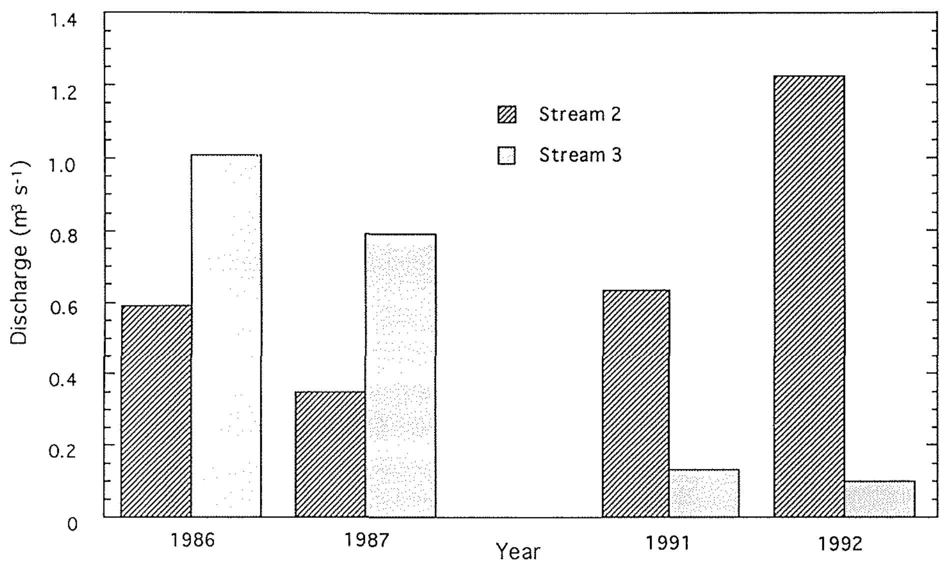

Fig. 2 The mid-summer average discharges of proglacial streams 2 and 3. The position of the streams did not significantly change between 1987 and 1992.

mass balance and hydrological research. The glacier-surface altitude has been repeatedly mapped since 1958 as part of the mass balance studies (Krimmel, 1989).

Since 1958, the glacier terminus has retreated about 425 m (Krimmel, 1994) and has lost about 23 m of water equivalent, averaged over the glacier surface. Most of the mass loss is in the ablation zone (Schwitter & Raymond, 1993). Consequently, large changes have occurred in the terminus region and the retreating glacier has revealed streams that once flowed directly into the proglacial lake from under ice.

From season to season, the number and exit location of the streams draining the glacier seemed to vary (Fountain, 1992; Vaughn, 1994). Occasionally, they have been observed to change position over just a few days. In 1982, only two streams appeared at the terminus and one had a much larger discharge than the other. By 1986, the glacier receded from a low bedrock ridge revealing two tributaries that formed the largest stream. One tributary, now known as stream 2, issued directly from the glacier and flowed over a low point in a bedrock ridge, and the other (stream 3) flowed along the terminus for about 70 m before joining the first stream at the low point (Fig. 1). Since that time, three streams have always flowed from the glacier. In 1986 and 1987, field observations showed that the three streams flowed from the glacier such that each stream drained one drainage basin within the glacier. The discharge of each stream was proportional to the drainage area, such that the largest stream drained the largest area (Fountain, 1992).

APPROACH

Shreve (1972) suggested that the direction of water movement in a glacier is governed by the fluid potential defined by the sum of the hydrostatic pressure of the overlying ice, and gravitational potential (elevation) of the water above a datum,

$$\Phi = \Phi_0 + \rho_w g z_b + \rho_i g (z_s - z_b) \qquad (1)$$

where Φ is the fluid potential, Φ_0 is the potential at the datum level (usually assumed zero at the stream gauging site) ρ_w and ρ_i are the densities of water and ice respectively, g is acceleration of gravity, and z_b and z_s are the elevations of the glacier bed and ice surface respectively. Equation (1) assumes that the water pressure in the hydraulic system is equal to the ice overburden pressure and is therefore constant. Generally, subglacial water pressures, indicated by the water level in boreholes drilled to the base of the glacier, are close to the overburden pressure of the ice (Fountain, 1994). Although the pressure varies over short time scales, the mean pressure is relatively constant over long time periods. The direction of basal water flow is defined by the gradient of equation (1).

Application of equation (1) requires knowing basal and surface topography of the glacier. Bedrock topography is available from Hodge (1979), who determined the thickness of the ice by radio-echo sounding. To date, nine maps of surface elevations of the glacier surface are available from a number of sources (e.g., Meier *et al.*, 1971; Krimmel, 1989, 1992, 1993; and unpublished data) and include the years 1958, 1961, 1964, 1970, 1977, 1980, 1985, 1991, and 1992. Krimmel (1989, 1992, 1993) compiled digital data files of bedrock and surface elevation maps with a 100 m interval between points. These files were used as input to equation (1) to form nine data sets of fluid potential, with ρ_w = 1000 kg m^{-3}, ρ_i = 900 kg m^{-3}, and g = 9.81 m^2 s^{-1}. Contours of equal potential were drawn using a numerical interpolation program, and the streamlines of fluid flow were estimated by drawing flow vectors perpendicular to the contours of fluid potential. Locations of flow divides were identified where the streamlines diverged.

RESULTS

For this paper, the drainage divides are presented for the years 1964, 1977, 1985, and 1992 (Fig. 3). The results are not exact, owing to the accuracy of the original data and the repeated interpolations to create the original maps, to create the digital data files, to contour the fluid potentials, and to produce the stream divides presented. Instead, we are concerned with the large-scale similarities and changes. Common to all maps are three distinct drainage basins that intersect the glacier margin and a smaller fourth basin, completely enclosed within the boundaries of the glacier. The enclosed basin is the result of a steep rise in the subglacial topography forming a bedrock knob (Hodge, 1976) that was first exposed in 1992. The focus of this paper are the changes of the two largest basins, the stream 2 and stream 3 basins, which drain most of the water from the glacier.

The drainage pattern for the largest basin remained consistent from 1964 through 1985. The accumulation zone of the glacier and a smaller fraction of the ablation zone drained through a narrow path in the ablation zone to what is now recognized as stream 3 (Fig. 3). In response to glacier thinning, the drainage divide on the east side of the glacier migrated up glacier. Between 1985 and 1992 the divide crossed the main part of the accumulation zone and shifted the main drainage area from stream 3 to stream 2. The shift must have occurred some time after the summer of 1987, when tracer injections revealed a drainage pattern similar to that theoretically predicted for the glacier in 1985.

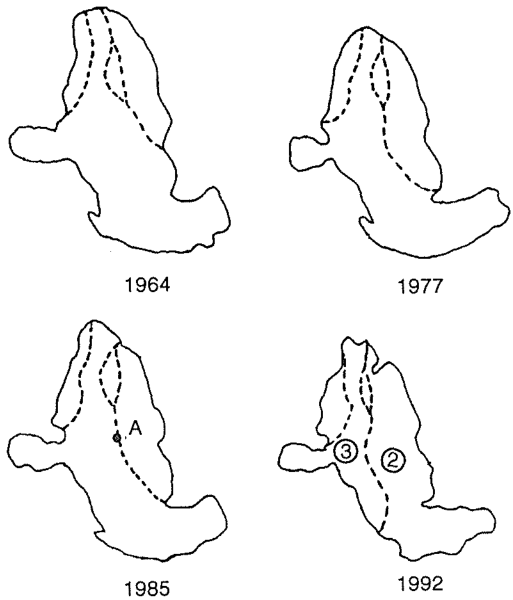

Fig. 3 Theoretical drainage patterns for four different years at South Cascade Glacier. The dashed lines indicate drainage divides.

DISCUSSION

The narrow drainage path to stream 3, identified by tracer injections in 1986/1987 is certainly the result of the long-term stability of the fluid potential field. A relatively narrow flow path has existed in that region since at least 1964. The concentration of flow into the narrow path probably results from conduit formation because no other process can explain the rapid movement of water through the narrow region (Fountain, 1992). Other evidence, including tracer dispersion and borehole water levels (Fountain, 1993, 1994) support the hypothesis that a conduit is present. Thus, we infer that a conduit has existed within the narrow drainage region since at least 1964. The difference between the narrow flow path, based on dye injections, and the wider subglacial flow path based on theoretical calculations probably results from the crevasse pattern on the glacier's surface that routes surface water into the body of the glacier. Crevasses in the narrow flow path are oriented parallel to the down-slope ice and water flow direction. Just outside the narrow path, crevasses splay away, directing water to adjacent basins on either side of the narrow flow path.

Farther upglacier, where the narrow path broadens, the drainage basin defined by the tracer injections widens to a much greater extent than the basin predicted in 1985 and looks more like the basin predicted for 1964 (Figs 1, 3). This difference is also thought to result from surface crevasses directing the surface input. Up-glacier from the fourth basin, crevasses are perpendicular to the ice flow direction and water can flow in the crevasses for some distance transverse to the position of a basal drainage divide. The difference between basal and surficial drainage paths was dramatically illustrated by a tracer injected in a borehole and another tracer injected into an adjacent crevasse (point

A in Fig. 3) (Fountain, 1993). The tracer injected into the borehole flowed into the basin predicted by the basal fluid potential, whereas the surface injection flowed to the adjacent basin.

The difference in position between the drainage divide revealed by surface injections of a tracer and that predicted from the basal fluid potential indicates that the orientation and slope of surface crevasses are important in determining the drainage path of water, in addition to the gradient of basal fluid potential. This result supports the observations of Stenborg (1968) on Storglaciären. Therefore, surface drainage divides may be offset from basal divides and drainage patterns of surface water reflect the routing processes at the glacier's surface, within the body of the ice, and at the base of the glacier. For South Cascade Glacier, basal divides are the more significant factor controlling water drainage patterns compared to surface crevasses.

The fourth basin, enclosed within the glacier perimeter, drains into the stream 2 basin as indicated by its inclusion in the stream 2 drainage pattern defined by the tracer injections. Theoretically, water from the fourth basin would flow along the drainage divide between the stream 2 and stream 3 basins and appear at the terminus as a fourth stream. Clearly, a small-scale irregularity in the basal topography, smaller than the resolution of the data used to define the basal topography, could shift the flow from the fourth basin into the stream 2 basin.

The changing pattern of drainage in South Cascade Glacier results from glacier thinning reducing the effect of the overburden pressure of the ice. Changes in drainage areas have caused changes in the relative discharge between streams 2 and 3 (Fig. 2). The shift in the drainage divide across the head of the glacier between 1985 and 1992 (Fig. 3), directed most of the surface flow to stream 2, causing it to become the largest of the outlet streams. Whether the increase in water flux has changed the subglacial hydraulic system in the stream 2 basin from a distributed condition in 1987 (Fountain, 1993) to a more conduit-like system today is uncertain.

The relatively rapid changes in observed stream position, where it exits the glacier, is probably caused by local topographic conditions. Near the terminus, where the ice is thin and the stream discharge is large, streams are likely to flow at atmospheric pressure (Hooke, 1984; Kohler, in press). The stream position is then defined by the lowest point of the local topography and the rate the stream migrates to the new position is governed by the rate of basal and ice erosion by the flowing water.

PREDICTION

The future drainage pattern of South Cascade Glacier was predicted by assuming that the volume loss from the glacier in the 7 years between the last mapping of the glacier (1985-1992) will be the same over the 7 years from 1992 to 1999. We subtracted the difference in surface altitude between 1985 and 1992 from the 1992 surface altitude to roughly predict the 1999 surface. If glacier thinning continues at the same rate, we predict a continuing shift in the drainage divide towards the west side of the glacier (Fig. 4). Consequently, the stream 2 will increase its drainage area and discharge at the expense of stream 3. The stream 3 drainage basin will maintain a narrow path through the lower ablation zone.

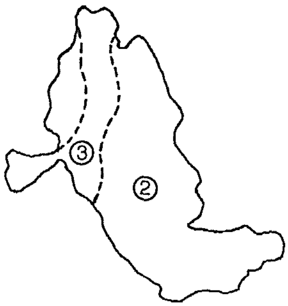

Fig. 4 The predicted drainage pattern for South Cascade Glacier in 1999. The dashed lines indicate drainage divides.

CONCLUSIONS

At South Cascade Glacier, the theoretical pattern of fluid potentials, derived from Shreve's (1972) equation for subglacial flow is consistent with the large-scale pattern of water drainage derived from dye-tracing studies. This conclusion agrees with the findings of Holmlund (1988) at Storglaciären, Sweden, Björnsson (1988) at Vatnajökull, Iceland, and Sharp *et al.* (1993) at the Haut Glacier d'Arolla, Switzerland. The number of drainage basins that intersect the terminus of the glacier generally predict the number of streams flowing from the glacier. However, basal topographic conditions near the terminus are an important factor in determining the direction of the water flow and may reduce or increase the number of streams observed.

Discrepancies between the predicted and observed drainage patterns in South Cascade Glacier are probably caused by local crevasse patterns, which may direct surface water input for some distance prior to entering the glacial hydraulic system. The unusually narrow drainage path in the lower ablation zone results from the pattern of basal fluid potentials and orientation of surface crevasses. The basal fluid potential directs subglacial water into a comparatively wide path through the middle of the lower glacier and local surface crevasses diverts surface water into adjacent basins except for a extremely narrow band of crevasses that route the water directly down glacier and into the middle drainage path.

Glacier thinning is changing the drainage pattern of water flow in South Cascade Glacier. This changing pattern is reflected in the changing discharge of the streams flowing from the glacier. If the glacier continues to thin, we expect that the drainage divide between the stream 2 and 3 drainage basins will continue to shift towards the west and that the stream 2 discharge will continue to increase at the expense of stream 3.

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